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Bioerosion, notch formation and micromorphology in the intertidal and supratidal zones of a calcareous sandstone stack

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Abstract

Variation in the magnitude of notch formation, and annual rates of bioerosion caused by *Littorina unifaciata* (Mollusca: Gastropoda) and *Clavarizona hirtosa* (Mollusca: Amphineura) with aspect and exposure, were assessed for the intertidal and supratidal zones of Shag Rock, a calcareous sandstone stack on the Western Australian coast near Fremantle. At eight profile stations around Shag Rock the gross morphology of the stack walls was surveyed and referenced to Australian Height Datum (AHD); the density of molluscs was established within discrete tidal and supratidal zones, and specimens taken for analysis of their gut contents. Molluscs accounted for approximately 1.1 cm^3 (Gastropoda) and 4.9 cm^3 (Amphineura) of inorganic material/yr per individual respectively. The highest rate of horizontal erosion was 0.8 mm/yr. This estimate is comparable with other estimates from Australia.

The visor and notch morphology varied systematically with aspect and exposure, with the notch being deepest, 2.0 to 2.3 m, on the exposed south and southwesterly profiles. The point of maximum notch formation corresponded with the highest density of molluscs on the rock face. It would have taken between 2 000 and 8 000 yrs of continued bioerosion at present rates of erosion for the notches to have formed. On six of the profiles, the morphology was further examined by measurement of surface roughness in 40 cm bands down the rockface. The highest roughness was recorded in the upper intertidal and supratidal zones, between AHD Zero and 0.8 m. This is consistent with the highest densities of *Clavarizona hirtosa*. Roughness decreased above and below this band. It increased again near the visor rim on the southerly and westerly profiles, where the upper part of the rockface is exposed to spray.

Introduction

Rates of erosion caused by two species of intertidal marine molluscs, *Clavarizona hirtosa* (Mollusca: Amphineura) and *Littorina unifaciata* (Mollusca: Gastropoda), were determined for intertidal and adjacent zones having markedly different aspect and exposure on a calcareous sandstone stack, Shag Rock, off Trigg Beach in Western Australia (Fig. 1). The objective of this pilot survey was to relate current rates of bioerosion to the morphology of the stack, particularly to configuration of the notch, as it varied with aspect and exposure.

It is well known that some marine molluscs cause direct erosion of the rock surface, as has been reviewed by Trenhaile (1980, 1987) and Spencer (1988). For example, North (1954) examined two Californian species of intertidal snail (*Littorina planaxis* and *Littorina scutulata*) (Mollusca: Gastropoda). He found that a 0.8 cm snail contained an average 1.6 mg of sand in the gut, and that the snails renewed their gut content 4-8 times daily. With a rock density of 2.2 g/cm^3, 100 snails of that size had the potential to excavate a basin of 86 cm^3/yr. Pioneering work was reported by Hodgkin (1964) from Point Peron, *ca* 45 km south of Trigg, Western Australia, and Norfolk Island in the southwest Pacific Ocean. He demonstrated that bioerosion was sufficient to have cut deep notches but not form shoreline platforms during the mid- to late Holocene. More recently, Hodgkin (1970) has described erosion caused by species of *Littorina* commonly known as periwinkles, as well as radula feeding marks characteristic of chitons (Mollusca: Amphineura). He found grazing marks as high as 70 cm above MHWS tide levels. Subsequent studies have supported Hodgkin's (1964, 1970) initial observations. Further reference to limestone erosion by molluscs was made by McLean (1974) for Barbados. Values of erosion for *Littorina* spp. of 0.15 and 0.4 cm^3/yr were established, while chitons gave values of 8.0 and 13.0 cm^3/yr. The combined amount of erosion by algal feeding gastropods and chitons suggested surface erosion and notch retreat in the intertidal zone of at least 2 mm/yr, which is approximately double the rate of erosion determined by Hodgkin (1964) from Western Australia and Norfolk Island. Trudgill (1983) has reported estimates of bioerosion, caused by grazing chitons, of between 0.2 and 0.7mm/yr. The rate of erosion associated with homesite excavation by chitons is an order of

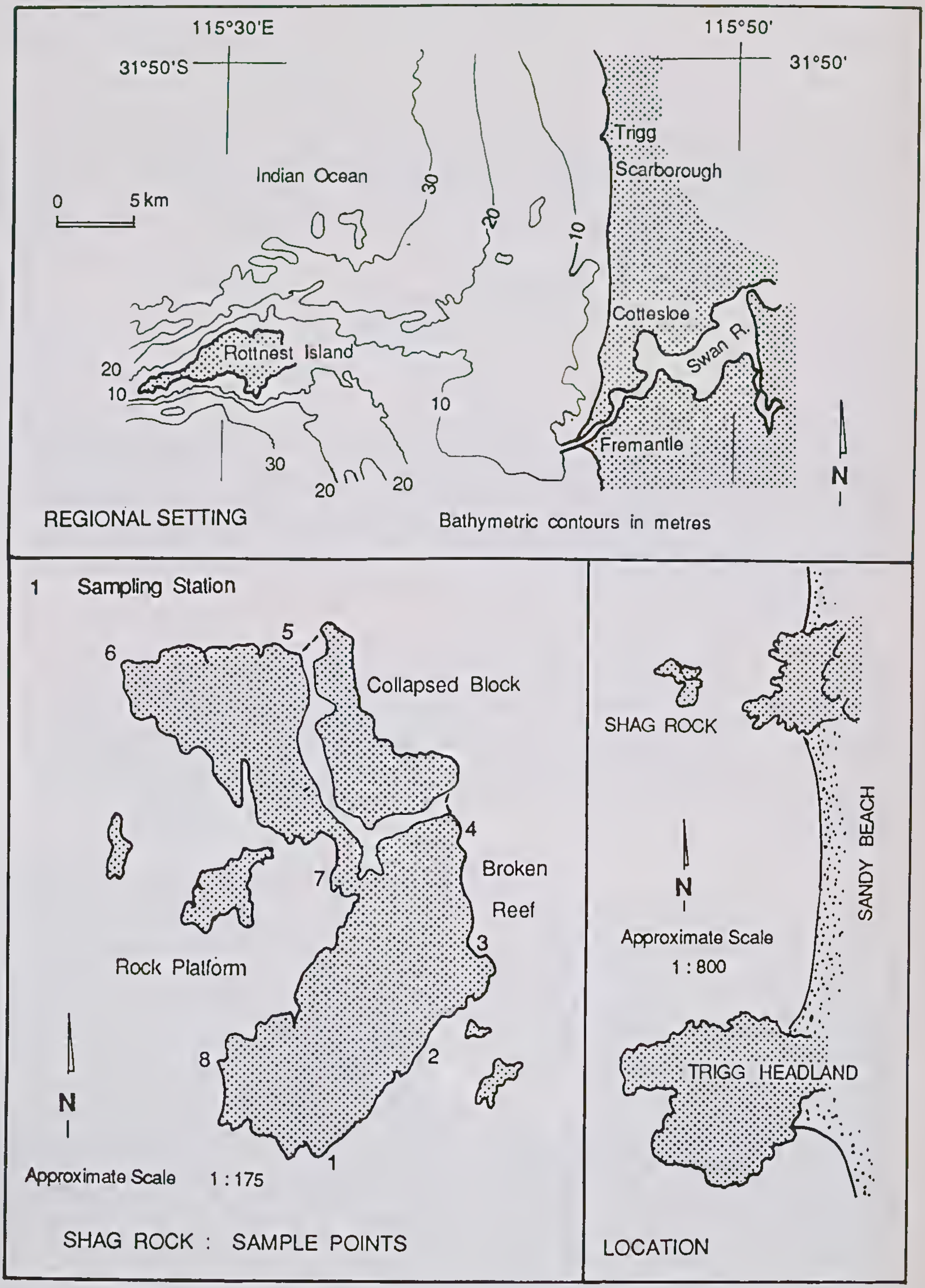


Figure 1 Regional setting and survey stations on Shag Rock at Trigg, Western Australia.

magnitude higher. McLean (1974) found that a typical homesite depression of a chiton (mean volume 55 cm^3) took less than 5 yrs to establish, and Trudgill (1983) reports chiton homesite excavation rates of 0.2 to 2.9mm/yr.

Intertidal marine organisms are very sensitive to desiccation. This results in zonal distributions, depending on degree of sensitivity (Hodgkin 1970, Lewis 1972). The abundance of animals and the rate of erosion will therefore vary with the duration and frequency of submergence. These factors are controlled by the tide and other sea level fluctuations, as well as the result of wave splash and spray, insolation characteristics, temperature fluctuations and nearshore variation in water chemistry (Stephenson & Stephenson 1949, Lewis 1972). Biological factors, including competition for food and space, trophic relations and predation (Paine 1980, Spencer 1988), also contribute to the zonation of marine organisms so that the distribution of bioerosion is probably not a simple relationship between the distribution of organisms and the physical parameters of the environment. Nevertheless, Evans (1968), working on the North American coast, found that rates of erosion within the intertidal zone increased with increasing exposure to sea water, and Hodgkin (1970) considered the rate of bioerosion fast enough to have cut notches up to 4 m deep during the Holocene. His proposition that bioerosion may account for a substantial proportion of notch development in limestone lithology is further examined here.

Study area

The limestone of the coast near Trigg is a coarse to medium grained calcarenite, composed of quartz sands and skeletal fragments, typical of the Tamala Limestone geologic unit described by Playford *et al* (1976). It includes Pleistocene marine and eolian sediments cemented in situ, chiefly by calcium carbonate, at a time when sea levels were lower than at present. The coastal limestones of the Perth Region are highly variable in calcium carbonate content, and hence in their hardness and strength, even within a small area (Tjhin 1981). They consist of both sandy calcarenite and calcareous sandstone, though at Shag Rock the latter predominates. Where it outcrops at the coast, the calcarenite has undergone several phases of marine erosion which has resulted in a distinctive assemblage of rock platforms, stacks, marine benches, beach ramps and low bluffs (Fairbridge 1950). The existing stacks and bluffs are now subjected to erosion by biological, chemical and mechanical agencies. This has resulted in the development of visors and intertidal notches similar to those described by Fairbridge (1950), Hodgkin (1964, 1970), Trudgill (1976) and Trenhaile (1980).

Shag Rock

Shag Rock is a small, calcareous sandstone stack on the northern perimeter of a 50 m wide rock platform. The stack rises to a maximum height of 2.1 m above MSL. Its upper surface slopes gently to the northeast. The stack is roughly V-shaped in plan form, with the V oriented towards the east (Fig. 1). There is considerable variation in the gross morphology of the walls of the stack with aspect and exposure. The visor and intertidal notch are best developed on the exposed northwest and southerly faces, particularly the latter. The notch varies from ca 0.6 m in depth inside the "V" to 2.5 m on the exposed southwesterly face. There is moderate visor development on the northern side of the stack, where the notch is ca 1.6 m deep. The leeward, easterly face is nearly vertical in some places and there are collapsed blocks in the channel between Shag Rock and the shoreline.

The biota of limestone platforms in southwestern Australia has been described by Hodgkin *et al* (1959), Marsh & Hodgkin (1962) and Black *et al* (1979). The dominant species at Shag Rock are *Clavarizona hirtosa* and *Littorina unifaciata*. Hence, they are the organisms examined. The molluscs apparently graze on an endolithic layer of cyanobacteria (*Oscillatoria* spp.) which covers the rock surface in the intertidal zone. Macro green algae (*Ulva lattuca*) are attached to the rock surface in some places.

Tides

Trigg is a microtidal environment (Davies 1980) where the coast experiences a mixed but predominantly diurnal tidal regime with a lowest to highest astronomic tidal range of 0.9 m (Anon 1988). Semidiurnal constituents are most apparent in the neap-tide phase when tidal ranges may be less than 0.1 m, whereas diurnal constituents dominate the spring-tide phase when the MLLW to MHHW range is approximately 0.4 m. The small tides of the region are frequently over-ridden by barometric pressure effects on sea level and by storm surge. The extra-tidal processes may at least double the range of sea-level variation due to the astronomical tides. Steedman (1977) reported that the extreme range of sea level recorded at Fremantle between 1896 and 1968 was 2.04 m, ranging from a low of 0.15 m below chart datum (recorded on 13 January 1896) to a high of 1.89 m (recorded on 10 May 1910). The passage of low-pressure systems may also generate long wave activity on the continental shelf (Allison *et al* 1980). These waves have periods up to 30 mins and amplitudes reaching 10 cm. The sea-level fluctuations combine to produce marked seasonal and lower frequency variation in submergence of the rock faces at Shag Rock.

In the context of this paper the term 'intertidal zone' refers to the area of rockface between MLLW and MHHW (Fig. 2) as the tidal levels are defined in the Australian National Tide Tables (Anon 1988). Upper and lower components of this zone are recognised in relation to MSL (AHD Zero) and the 'supratidal zone' is loosely taken to represent the zones of highest astronomical tide ranging, surge inundation and wave splash. Under storm wave action, wave splash occurs to the roof of the notch, at least, and spray covers the crest of the stack. The definition of the supratidal zone used here is consistent with the term 'supralittoral fringe' used by Lewis (1964). In both instances the upper limit of the zone is set by the upper limit of *Littorina* spp.

Waves

In the vicinity of Trigg, the Western Australian coast is dominated by a low- to moderate-energy deep-water wave regime characterised by a persistent south to southwest swell (Silvester 1976). Waves measured in deep

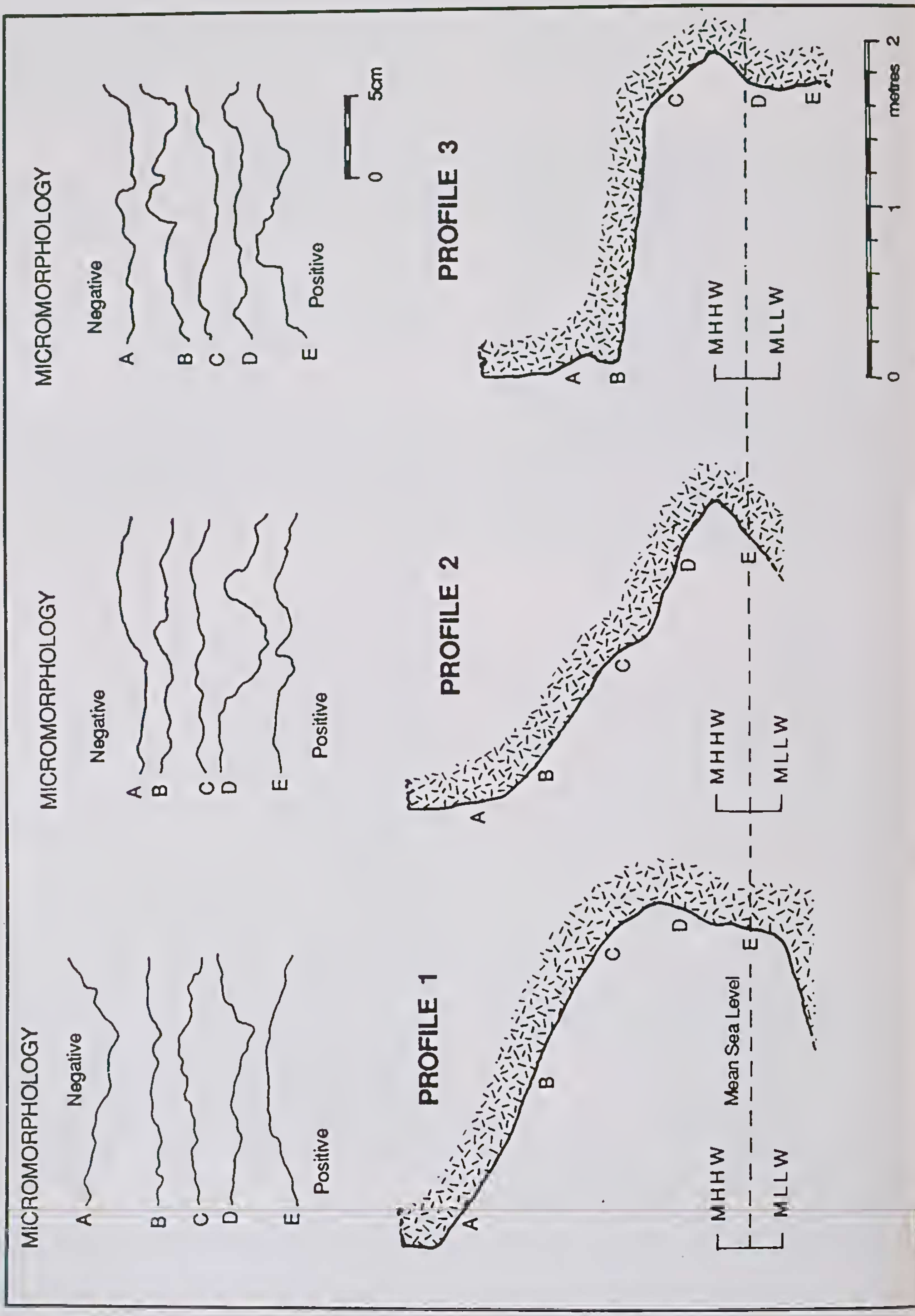
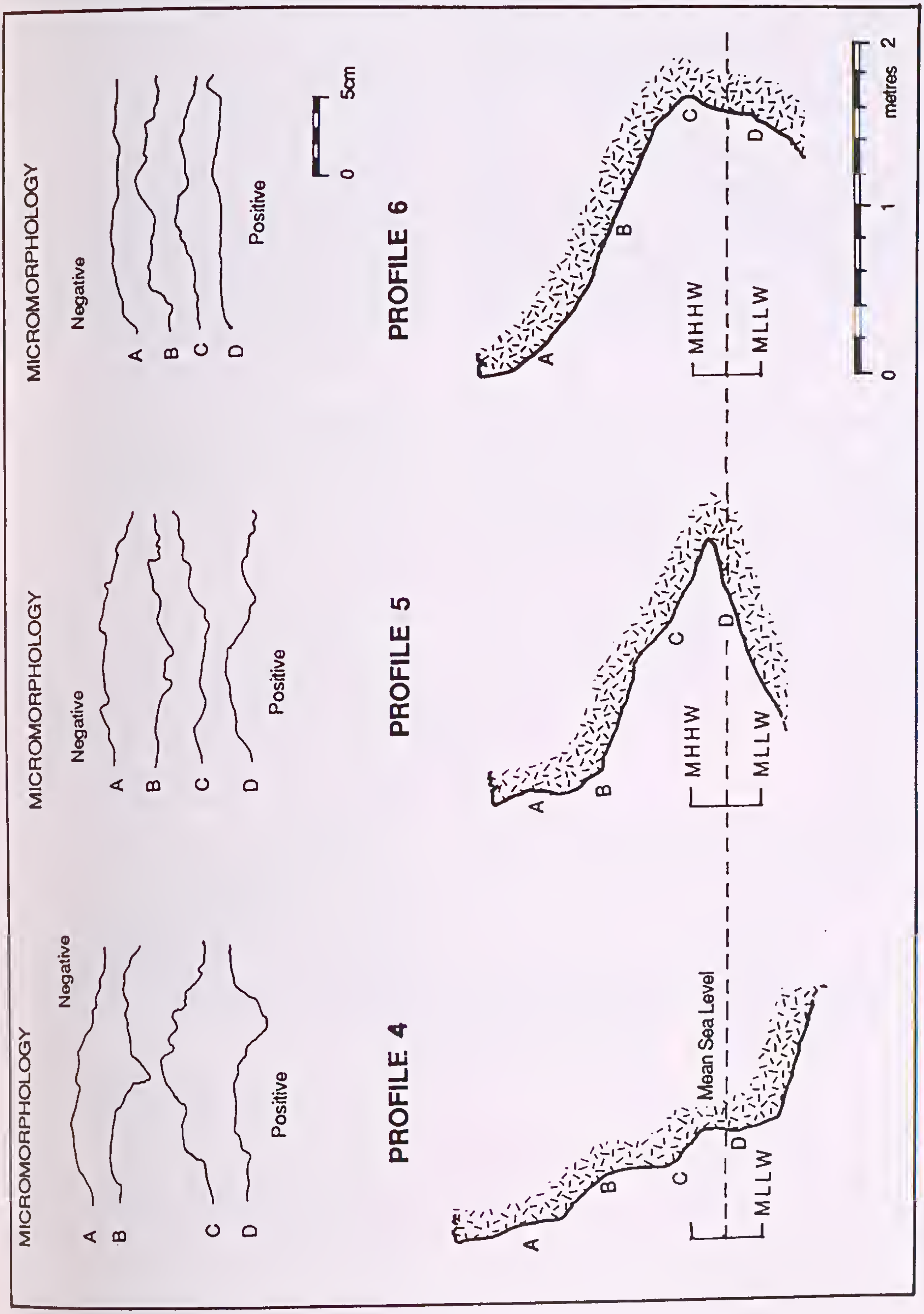


Figure 2 Profiles of rock faces at Shag Rock. The profiles show the diversity of visor and notch formation around the stack as well as micromorphologic variation within each profile. The positive face is exposed to the atmosphere.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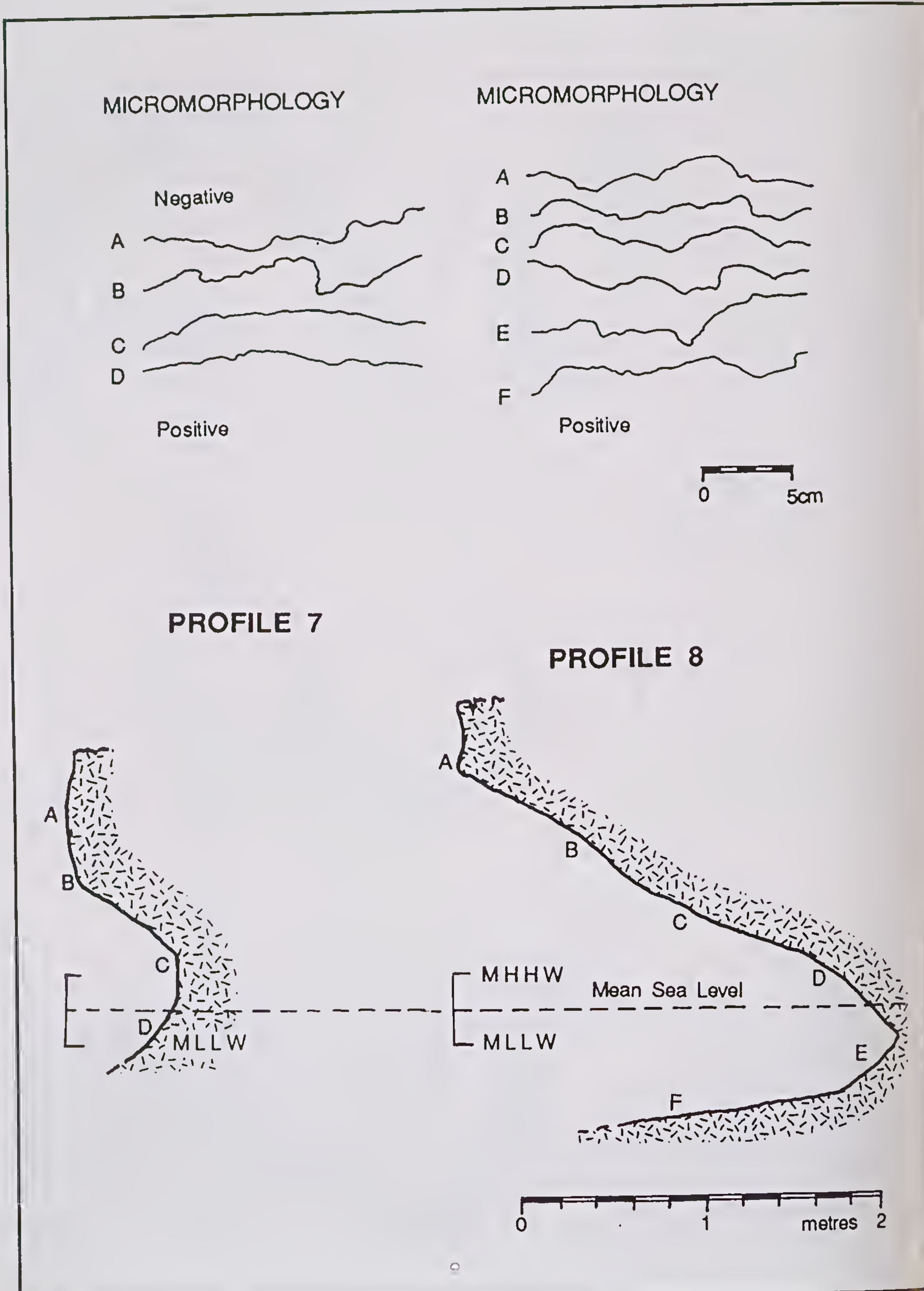
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water off Garden Island (Steedman 1977, Riedel & Trajer 1978) and inside the reefs at 10 m depth off Mullaloo Point had median significant heights of 1.4 and 0.4 m, respectively, modal maximum heights of 2.0 - 2.5 and 1.0 - 1.5 m, respectively, and modal periods of 6 - 7 secs in both instances. Wave conditions at Trigg fall within these bounds. There is little variation in the low wave energy from year to year for the period December through May (summer to autumn). However, the wave climate is more severe between May and November (winter to spring), with large variations possible between successive years. At Trigg, waves break over the seaward margin of the rock platform under all but very low tide and wave (H_{max} < 0.5 m) conditions and Shag Rock is generally hit by surf bores travelling across the shoreline platform rather than by breaking waves. Hence, mechanical wave erosion would be less than might occur under shock pressures generated by waves breaking against the stack.

Materials and methods

The study was carried out over a three-week period during July and August 1985. Profiles of the rockface (Fig. 2) were obtained by measuring the vertical and horizontal components from a plumb line at eight positions around the upper rim (visor) of the rock (Fig. 1). The profiles were later tied to a fixed benchmark and related to Australian Height Datum (AHD) by means of a closed survey traverse.

The grazing action and homesite excavation of biolithofagic organisms potentially leads to variation in the micromorphology of the rock surface. For example, chitons and sea urchins excavate different shaped homesites (McLean 1974, Trenhaile 1987). The micromorphology of the rock face on each profile (Fig. 2) was surveyed by using a Temco Template Former. The surface irregularity was expressed in terms of a Roughness Coefficient (RC) following Barton & Choubey (1977). Each coefficient was calculated as the standard deviation of surface elevation measured at 2 mm intervals along 15 cm long profile segments in 40cm bands down the rockface. The elevations were detrended prior to calculation of the variance.

In conjunction with the micromorphological surveys, a Schmidt Hammer (Barton & Choubey 1977) was used to establish the shear strength of the rock surface at three profile stations. It was considered that measurement of shear strength could provide an indication of the susceptibility of the rock surface to bioerosion. Barton & Choubey (1977) recommended that 10 readings per surface area be taken, the lowest five discarded and the mean of the highest five accepted as an indication of shear strength. Their recommendations were followed for the survey on Shag Rock.

Within each face, vertical zones were identified on the basis of the distribution, abundance and species of mollusc present as well as by the morphology. In turn, these were related to AHD. The upper zone was an area which extended ca 50 cm downwards from the visor and coincided with low densities of *Littorina unifaciata*, the only species present; the middle zone was located in the central area of the overhang and contained higher densities of *Littorina unifaciata* only; the lowest zone coincided with the notch. It lacked *Littorina unifaciata* but was inhabited by *Clavarizona hirtosa*. The lowest zone was extended to well below MSL in some instances. Molluscs were collected from 20 x 20 cm quadrats which were placed randomly within each zone on each of four profiles. Three quadrat samples were made in each instance, yielding a total of thirty-six, 20cm^2 samples. The insoluble content of the mollusc digestive tracts (largely quartz sand particles) were determined by following the procedures described by McLean (1974) and Ayre *et al.* (1977).

An estimate of bioerosion in the upper and lower intertidal and supratidal zones was calculated in three steps. The average, insoluble gut content was multiplied by four to obtain the daily, and hence annual, rates of ingestion, following North (1954). This was then converted to a volumetric erosion rate by considering mollusc densities for 20cm^2 quadrat samples. Rates of surface erosion in mm/yr were then estimated on the basis that 2.2g of rock equals 1cm^3 in volume.

Results

Macromorphology

The upper surface of the stack has a northeasterly slope so that the crest of the visor is highest (2.1 m) in the southwest and lowest (1.3 m) to the northeast. The overhang varies in shape with aspect and exposure to wave and current activity (Fig. 2). The notch is deepest (2.0 - 2.3 m) on the south and southwest profiles and least on the western wall, inside the 'V'where it is 0.65 m deep. The deepest part of the notch is apparently related to exposure to the prevailing wind, surf bore, wave splash and current activity. In general, the elevation of the notch is close to the upper tidal zone. It lies between 0.1 m and 0.2 m above AHD Zero on most profiles. Exceptions to this occur on the southern profile, where the deepest point is 0.6 m above, and on the eastern profile where it is 0.5 m below, AHD Zero. The exceptions respectively correspond with the most exposed and protected aspects of the stack.

Micromorphology

The highest roughness coefficients were recorded in the upper intertidal and supratidal zone, between AHD Zero and 0.8 m (Table 1). Roughness decreases above and below this band. It increases again near the visor rim on

Table 1

Surface roughness coefficients. Each coefficient was calculated as the standard deviation of detrended surface elevations measured at 2mm intervals along a 15cm profile segment. E = Elevation of segment centre above Australian Height Datum (m). R = Roughness coefficient (mm); — = no data.

Distance below rim of visor (cm)	Aspect							
	Profile 1 (South)		Profile 3 (East)		Profile 6 (North)		Profile 8 (S-West)	
	E	R	E	R	E	R	E	R
40	1.6	5.3	1.2	5.7	1.0	3.1	1.3	10.8
80	1.2	3.3	0.8	6.0	0.6	6.5	0.9	5.1
120	0.8	15.3	0.4	3.5	0.2	13.1	0.5	13.4
160	0.4	4.9	-0.1	6.1	-0.2	3.2	0.1	5.5
200	0.0	6.0	-0.5	5.1	—	—	-0.3	7.2

the southerly and westerly profiles, where the upper part of the rockface is exposed to spray. High values were also recorded in the lower intertidal zone of profiles on the southern half of the stack. With the exception of the sheltered eastern profile, the zone of greatest roughness on each profile was coincident with the highest densities of *Littorina unifaciata* and the roughest profiles were those facing to the west and southwest.

Estimates of rock hardness determined by Schmidt Hammer, point-load testing at Shag Rock indicate a very low shear strength . The Schmidt Hammer values ranged from 1.0 to 3.3, without systematic distribution. The results are apparently due to the very low calcium carbonate content (27.8%) of the calcareous sandstone comprising the stack. They indicate the susceptibility of the rock to erosion but are too low to facilitate a valid analysis of differential rates of surface erosion and notch retreat.

Bioerosion

Littorina unifaciata and *Clavarizona hirtosa* showed distinct vertical stratification, and hence were used as a factor in identification of zones for sampling. The principal variation in density was related to aspect. The gastropods clearly preferred the middle zone of the easterly and southerly faces (Table 2) whereas aspect appeared not to affect chiton density.

Littorina unifaciata samples were found to contain a mean value of 1.3 mg of inorganic material per individual (mean length of snails 5 mm). Assuming an average turn-over of stomach contents of four times/day (North 1954), 1.9 g of surface rock would be removed every yr by each snail. This compares with 8.8 g/yr for *Clavarizona hirtosa* (mean length 33 mm), assuming the same daily rates of stomach turn-over. Chiton specimens contained a mean of 6.0 mg of inorganic material per individual (Table 2).

The calculated rates of erosion (g/yr) were then used to assess rates of notch retreat (mm/yr). Erosion rates in the upper intertidal zone ranged from 0.2 mm/yr on the northern profile, to 0.8 mm/yr on the southern profile (Table 2). Erosion rates were generally highest in the south-eastern part of the stack. In the lower intertidal zone, erosion rates were less variable, ranging from 0.4 mm/yr on the east profile, to 0.5 mm/yr to the west. Assuming that bioerosion commenced on a near vertical surface, and that the current rate of bioerosion has been constant, an estimate was made of the time required to account for the notch formation observed at each face on the stack. The amount of time required for maximum notch formation at the estimated rate of erosion varied from ca 2 000 yrs for the east face (Profile 3), to 8 000 yrs for the north face (Profile 7). The estimates are indicated in Table 2.

Discussion

Although assumptions underlying the formation of notches at Shag Rock are somewhat sweeping, the estimated rates of surface erosion and notch retreat are consistent with rates of bioerosion reported elsewhere. A mean of 1.1 cm^3/yr for *Littorina unifaciata* at Trigg compares with 0.8 cm^3/yr reported for a Californian species of *Littorina* (North 1954). Similarly, a value of 4.9 cm^3/yr for *Clavarizona hirtosa* at Trigg compares with 8 cm^3/yr suggested for a species of chiton by McLean (1974). Homesite excavation of *Clavarizona hirtosa*, reportedly accounting for ca. 10 cm^3/yr per individual chiton (McLean 1974), was not taken into account although variation in micromorphology indicates that this might be significant. The estimated range of surface erosion and notch retreat of 0.2 mm to 0.8 mm (Table 2) compares very closely with rates of 0.2 mm to 0.7 mm reported by Trudgill (1983) for an intertidal limestone feature on the Great Barrier Reef. The rate of erosion by non-biotic

Table 2

Mollusc densities and distribution; annual rates of bioerosion (g/yr); annual rates of surface erosion and notch retreat (mm/yr); and the estimated time for the notch to have been cut by bioerosion (yrs) for supratidal, upper and lower intertidal levels on the rock face. The intertidal zones are defined with respect to Australian Height Datum (Fig. 2)

Aspect	Tidal zone	Mollusc no.s/20cm² Amphineura	Mollusc no.s/20cm² Gastropoda	Annual erosion (g) Amphineura	Annual erosion (g) Gastropoda	Annual erosion rate (mm)	Depth of notch (m)	Time for notch to form (years)
Profile 1 (South)	Supra	0.0	7.0	0.0	13.5	0.15	0.0	0.0
	Upper	0.0	35.3	0.0	68.1	0.76	1.6	2 000
	Lower	4.3	0.0	37.7	0.0	0.42	1.9	4 750
Profile 3 (East)	Supra	0.0	13.3	0.0	25.7	0.28	0.0	0.0
	Upper	0.0	29.3	0.0	56.4	0.63	1.7	2 833
	Lower	4.0	0.0	35.1	0.0	0.39	1.7	4 250
Profile 6 (North)	Supra	0.0	0.0	0.0	0.0	0.00	0.0	0.0
	Upper	0.0	7.3	0.0	14.1	0.15	1.6	8 000
	Lower	4.6	0.0	40.4	0.0	0.45	1.5	3 000
Profile 7 (West)	Supra	0.0	0.0	0.0	0.0	0.00	0.0	0.0
	Upper	0.0	7.6	0.0	14.7	0.16	0.8	4 000
	Lower	5.0	0.0	43.9	0.0	0.49	2.6	5 200

processes, such as those reviewed by Trenhaile (1987) and Spencer (1988), are arguably greater in areas where surface roughness is greatest and exposes a larger surface area to mechanical and chemical processes (McLean 1974).

It is questionable whether the rate of bioerosion can be used to explain the depth of the notch for different levels on the rockface, assuming that the calculated erosion rates have been consistent in the past and that erosion commenced on a near-vertical face. The wide range of estimates of surface erosion from different faces on the stack indicates that other factors may contribute to notch retreat. Notch formation is also facilitated by physical and chemical agencies (Trenhaile 1987) which were not considered in this survey. Also, less obvious effects of bioerosion have been pointed out by McLean (1974). These include an increase in the surface area of rock exposed to mechanical and chemical weathering as well as reduction of the resistance of the rock surface to mechanical processes. On Shag Rock, the surface roughness varied systematically with location with respect to tidal level and with the distribution of the biota. The roughness was greatest in the lower intertidal zone (Fig. 2). It decreased towards the visor. Shear resistances, recorded as Schmidt Hammer impacts, were highest in the supratidal zones.

The findings of this study are generally consistent with Hodgkin's (1964, 1970) time estimate for Holocene notch formation. His contention was that bioerosion was fast enough to have cut notches up to 4 m deep during the Holocene but was not of sufficient magnitude to explain the formation of shoreline platforms. This was also the case at Shag Rock. If present-day sea levels and current rates of bioerosion were stable over the last 6 000 yrs, all the other erosive agents would account for less than half the material eroded from the stack during that period, given the somewhat unreasonable assumption of near vertical faces on the stack. Profile determinations of the south and west faces, where the undercut was measured to sufficient depth, show that bioerosion is greatly reduced below the low water mark (Fig. 2).

The extent of wave-induced erosion may not be immediately apparent. While, for instance, erosion is consistently more extensive near the notch and less marked near the visor, the suggested rates of bioerosion could account for that. Evans (1968) commented on the highest point of the notch usually being level with the high water mark. There is considerable diversity in location of the notch with respect to mean sea level (AHD zero) at Shag Rock (Fig. 2). The maximum horizontal extent of the notch occurs approximately at MLLW level on Profile 8. It is within the intertidal zone on Profiles 4 and 5; at MHHW on Profiles 2, 3 and 6; and above MHHW elsewhere. This variation may reflect reduced mollusc densities (Table 2) rather than reduced wave energy, although the notch tends to be lowest on the leeward side of the stack. A maximum rate of notch retreat of 0.6 mm/yr for the sheltered east face compares with 0.8 mm/yr for the exposed south face. Nevertheless, the north face can be expected to be the most protected under the prevailing south-westerly wave regime and its relatively low rate of surface erosion of 0.5 mm/yr may reflect this. Considering exposure to wave energy as an indication of the source of maximum physical erosion, the exposed south and west faces should be expected to show deeper notches than the relatively sheltered north and east faces, as is the case at Shag Rock.

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